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Dragana Vukovic[1,2], Christophe Peucheret[3], Leif Katsuo Oxenløwe[2],
Chang Joon Chae[4], Duk-Yong Choi[5], and Mark D. Pelusi[1]

[1]*Centre for Ultrahigh bandwidth Devices for Optical Systems, School of Physics, University of Sydney, NSW 2006, Australia*
[2]*DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*
[3]*FOTON Laboratory, CNRS UMR 6082, ENSSAT, University of Rennes 1, 22305 Lannion, France*
[4]*National ICT Australia, Department of Electrical and Electronic Engineering, University of Melbourne, VIC 3010, Australia*
[5]*Australian National University, Laser Physics Centre, Canberra, ACT, Australia*
e-mail: drvu@fotonik.dtu.dk

***Abstract*—All-optical wavelength conversion of 80 Gb/s RZ-DPSK polarization multiplexed signals is demonstrated in a silicon nanowire using an angled-pump scheme. The quality of the converted signal is characterized through BER measurements for the first time.**

Keywords— Silicon nanowires; four-wave mixing, polarization-multiplexed signals.

I. INTRODUCTION

All-optical signal processing in silicon nanowires has attracted significant research interest in recent years [1,2]. Some attractive features of Si nanowires are superior nonlinearity (thanks to the high nonlinear refractive index and the strong optical mode confinement), flexible dispersion control, and fabrication compatible with complementary metal-oxide-semiconductor (CMOS) technology. All-optical wavelength conversion, as an important feature in future wavelength division multiplexing (WDM) networks, has been successfully performed using silicon nanowires. However, due to their strong birefringence, signal processing in both TE and TM polarization simultaneously is difficult to achieve. This makes wavelength conversion challenging to perform, especially for polarization multiplexed (Pol-MUX) signals, which future telecommunication networks will use to double the data capacity by transmitting different signals at the same wavelength on two orthogonal polarization states in optical fibres. Previously, it has been shown that silicon waveguides can be used for wavelength conversion of Pol-MUX signals, although only at a low bit rate of 20 Gb/s for amplitude-shift keying (ASK) signals [3], and without any bit error ratio (BER) measurement validation.

In this paper, all-optical wavelength conversion of high speed 80 Gb/s Pol-MUX return-to-zero differential phase-shift keying (RZ-DPSK) signals is experimentally demonstrated using four-wave mixing (FWM) in an angled-pump scheme [4,5]. The performance of the converted signal is characterized through BER measurements for the first time. Measured BERs well below the forward-error-correction (FEC) threshold are achieved.

II. OPERATIONAL PRINCIPLE AND EXPERIMENTAL SETUP

The efficiency of wavelength conversion by FWM is maximized when the pump and signal waves at different wavelengths are co-polarized. For Pol-MUX signals, the Jones vector of the pump can be decomposed on an orthogonal basis coinciding with the eigenstates of polarization of the waveguide as it is shown in Fig. 1(a). The challenge here is to make the wavelength converted signals for both Pol-MUX tributaries to have equal power due to different propagation properties of the two different modes. For the 15 mm long silicon nanowire used in the experiment, the linear insertion loss was measured to be around 6.4 dB when coupling to the TM mode, and 12.7 dB for the TE mode. The dispersion for the TE and TM modes was calculated using a vectorial finite-difference mode solver [6], and found to be 413 ps/nm/km and -19615 ps/nm/km, respectively, around 1550 nm.

In this experiment, each polarization tributary of the Pol-MUX signal was aligned with either TE or TM mode of the waveguide, as shown in Fig. 1(b), in order to minimize the impact of the differential group delay (DGD), which is present due to strong birefringence in the waveguide. The SOP of the pump was carefully adjusted in order to equalize the FWM process for each polarization tributary in the TE and TM modes of the waveguide. The waveguide embedded in SiO_2 had a 220 nm × 460 nm cross-section, and was equipped with inverse tapers to decrease coupling loss to tapered fibres to 2.5 dB/facet.

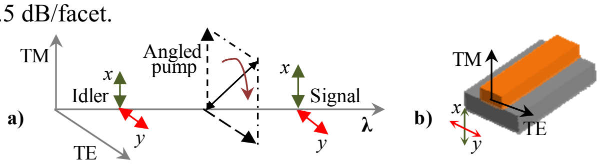

Fig 1. (a) Operational principle for angled-pump wavelength conversion for a Pol-MUX signal. *x* and *y* represent the two polarization tributaries. (b) Signal polarization setting with respect to the waveguide axes.

The wavelength conversion setup is shown in Fig. 2. The 80 Gb/s Pol-MUX RZ-DPSK signal was generated from a continuous wave (CW) laser emitting at 1551.5 nm. This was modulated by a pair of Mach Zehnder modulators (MZMs). The first MZM served as a pulse carver, and the second as a data modulator. The data modulator was driven by a 40 Gb/s 2^{31}-1 long pseudo-random binary sequence (PRBS). Polarization multiplexing was emulated by splitting the signal, delaying one data stream with respect to the other by ΔT, and then recombining them with orthogonal polarizations in a polarization beam splitter (PBS). The signal was further amplified in an erbium-doped fiber amplifier (EDFA) followed by a 1 nm optical band-pass filter (OBPF). The pump

The authors acknowledge financial support from Villum Fonden via the NATEC center.

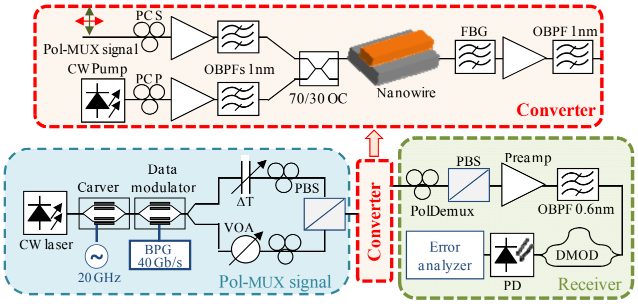

Fig 2. Experimental setup for AOWC of a 80 Gb/s polarization multiplexed RZ-DPSK signal. (VOA – variable optical attenuator)

for FWM was generated from an external cavity CW laser at 1549 nm wavelength, amplified in an EDFA and filtered by a 1 nm OBPF. The SOP of both the pump and signal were controlled by polarization controllers P and S, respectively, as shown in Fig. 2, and combined in a 70/30 optical coupler (OC). At the output of the nanowire, the wavelength converted signal was filtered using a fibre Bragg grating (FBG) filter to block the pump, and an additional 1 nm OBPF to select the idler. After filtering, the polarization of the converted signal was first demultiplexed with a PBS and input into a conventional optically pre-amplified receiver. The receiver consisted of an EDFA, a 43 GHz DPSK demodulator (DMOD), a 0.6 nm OBPF and a single photodetector (PD). The demodulated idler was further input to a 40 Gb/s error analyzer for BER measurements.

III. Experimental Results

The performance of the converted signal was characterized through BER measurements as a function of the average received power, as shown in Fig. 3(a). The back-to-back (B2B) performance was measured by connecting the receiver to the output of the data modulator, and compared with the BER of the converted signal. At first, the BER was measured with only one polarization tributary of the Pol-MUX signal present in the waveguide and the pump co-polarized to the signal. In this case, the FWM process is most efficient. The signal power at the waveguide input was around 71 mW, while the pump power was 231 mW. Due to the non-linear loss in the waveguide, the total insertion loss was increased by 4 dB. The conversion efficiencies, defined as the ratio between the idler power and the signal power at the output of the waveguide, of the TM and TE modes were -22.5 dB and -32.8 dB, respectively. The power penalty at a BER of 10^{-9} was only 1 dB for the signal in the TM mode. When the signal was aligned to the TE mode of the waveguide the power penalty was 3 dB. This additional penalty is due to the lower FWM conversion efficiency reducing the optical signal-to-noise ratio (OSNR) at the receiver.

Next, both tributaries of the Pol-MUX signal were launched into the waveguide keeping the same power levels. Each polarization tributary of the signal was aligned with either TE or TM mode of the waveguide. The SOP of the pump was aligned so that the idler power was the same for both input polarizations. This power was monitored by switching off one of the polarization tributaries of the Pol-MUX signal. The spectra at the input and output of the device are shown in Fig. 4. The overall conversion efficiency for the combined power of both Pol-MUX tributaries was measured to be -29.7 dB. It should be noted that the total pump power

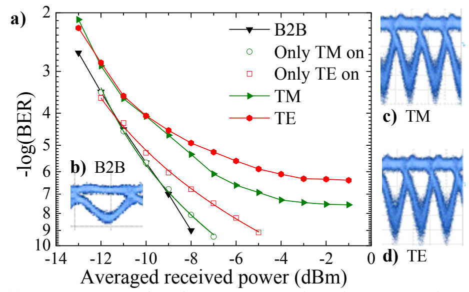

Fig. 3. (a) BER curves for the B2B, wavelength converted 40 Gb/s RZ-DPSK TE and TM tributaries when only one (hollow symbols) or both (full symbols) tributaries are input in the waveguide. Eye diagrams for (b) B2B signal at -8 dBm received power, (c) converted TM signal, (d) converted TE signal at -2.5 dBm received power.

interacting with each tributary of the Pol-MUX signal was divided between the two polarizations modes of the waveguide. Similarly, the signal power per tributary was only 35.5 mW. The degradation of the BER (shown in Fig. 3(a)) compared to the single polarization case is due to the combination of the much lower idler power degrading the OSNR, and the cross-talk between the two polarization channels taking place in the waveguide. Optimizing waveguide dimensions could result in similar loss properties for both modes and therefore improve overall performance. Nevertheless, both tributaries of the Pol-MUX signal showed a BER below 10^{-6}, which is well below the standard FEC limit assuming 7% overhead [7]. Error free detection is therefore possible at a net rate of 74.8 Gb/s. Fig. 3(c)-(d) show the received 40 Gb/s eye diagrams demultiplexed from the 80 Gb/s wavelength converted Pol-MUX RZ-DPSK signal.

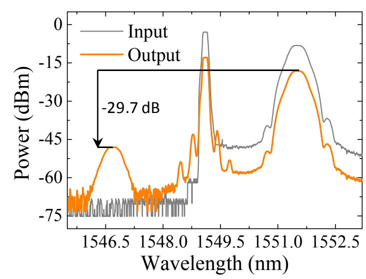

Fig. 4. Spectra at the input and output of the Si nanowire (0.1 nm resolution) for Pol-MUX input signal.

IV. Conclusion

All-optical wavelength conversion of an 80 Gb/s polarization multiplexed RZ-DPSK signal is demonstrated experimentally based on FWM in an angled-pump scheme. By optimal alignment of the pump, equal idler power levels were obtained for both polarization multiplexed tributaries. BER characterization was performed for the first time. Both polarization multiplexed tributaries achieved performance well below the standard FEC limit.

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